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How an Innovative Membrane Brought a Vision to Life

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Abstract

The new Piotrkowska Street tram stop canopy is a striking and elegant addition to the historical city centre of Łódź (Poland), a town once referred to as the “Polish Manchester” due to the rapid growth in industry growth during the 19th century. The canopy, inspired by Art Deco style, was imagined as a steel structure incorporating an intricate geometry and featuring a roof covered with panels of coloured glass.

The paper describes the evolution of the project and explains the design process involving 3d parametric modelling and optimization of both the geometry and materials. It shows the challenges of the structural design originating from two opposing interests – the Architect’s aesthetical vision and the Contractors requirement for cost efficiency. To help realize the Architect’s complex vision and deliver an optimized final product BuroHappold Engineering came up with an innovative solution, for which the outcome was a change of heavy glass panels to unconventional single layer ETFE. The paper explains the pre-stressed foil’s benefits and the risks related to its application in a climate where snow load is often a governing case.

The paper also highlights the advantages of parametrical design techniques; its flexibility and its consistent accuracy. It shows how the design process can be time efficient, and how inevitable changes can be implemented almost effortlessly even into models which are derived from complex geometry.

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1. Introduction

The modernisation of the East-West express route road running through the city of Łódź (Poland) completed in 2015 not only impacted the organisation of car traffic but also the public transportation system. One of the most significant changes affected the tramway network, a popular means of transportation for all. This was reorganised such that the main tramway tracks (East-West and North-South) meet in the heart of the city and share a single tram station with four separate platforms. This is a convenient improvement for the commuters in Łódź which enables them easy interchange between different tram lines.

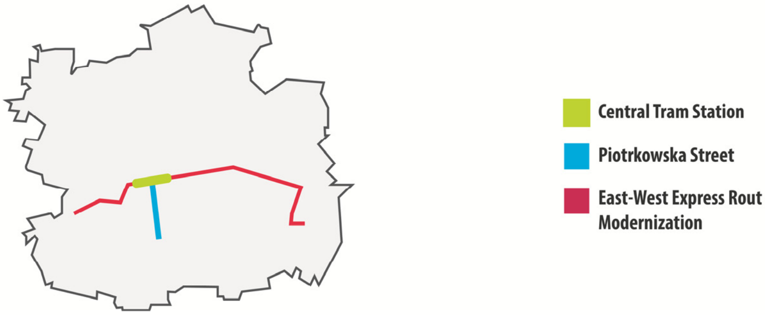

Fig. 1. The city plan and a scope of modernisation.

In order to improve comfort, a roof canopy was envisioned covering all four platforms to protect waiting passengers from wind, rain and snow. This small yet conspicuous part of the whole modernisation became the centrepiece of the investment, owing mainly to the outstanding architectural form. The canopy aimed not only to serve as a shelter for commuters, but also as a beacon luring citizens and tourists to the most renowned historical part of the city, the Piotrkowska Street.

This paper explains how this goal was achieved thanks to the application of a novel structural skin.

2. General description of the canopy structure

The Piotrkowska Central Tram Station canopy is a steel structure made of CHS profiles. It is approximately 100 m long, 32 m wide and 13 m high. It consist of three similar parts, each 33 m long, defined by two transverse movement joints located along the longitudinal axis of the canopy.

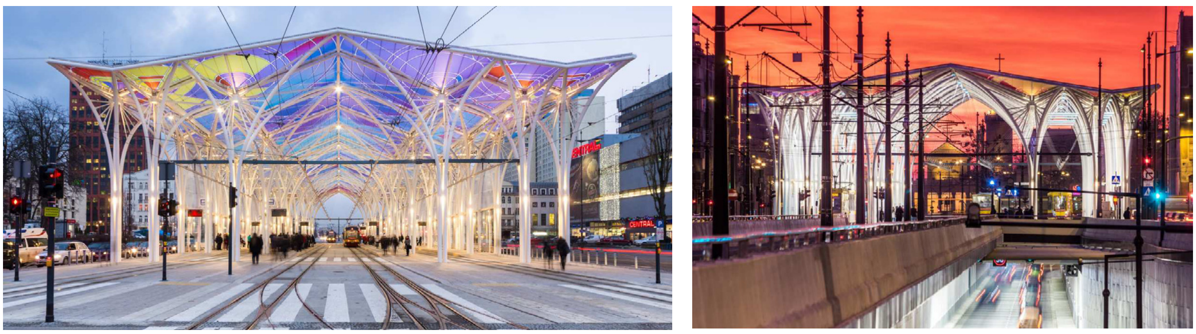

Fig. 2. (left) The Piotrkowska Central Tram Station from the pedestrian perspective; (right) The canopy over the express route tunnel.

The roof, spanning over four tram tracks and four platforms, is supported by columns and arcs arranged in regular rows with spacing from 2.3 m up to 13.2 m. Two middle rows of columns are supported on the express route tunnel structure, while the remaining columns on the outside have their own foundations. The steel grid of the roof structure serves as a support for tramway traction and lighting.

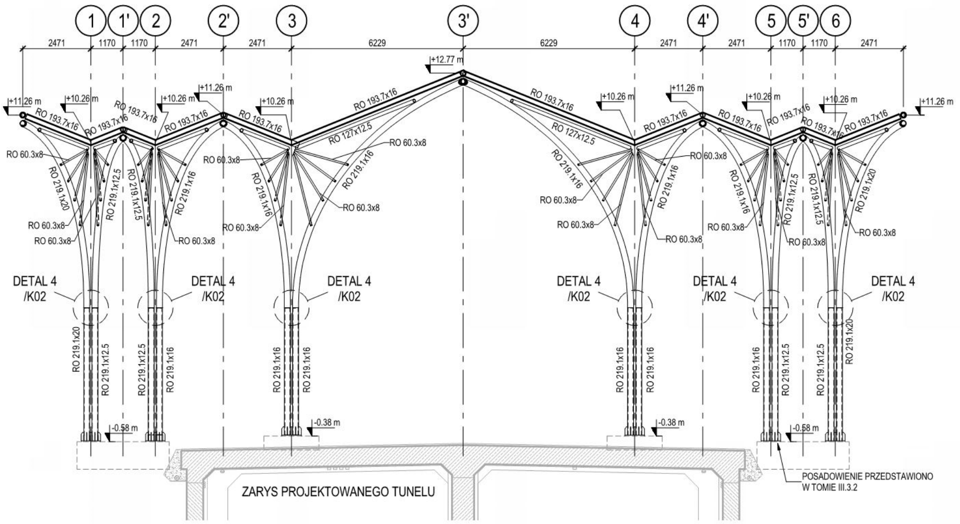

Fig. 3. A transverse section through the Piotrkowska Central Tram Station structure (from the Building Permit stage).

A single layer ETFE membrane was applied to the roofing and the façade. Use of the membrane was restricted to the higher parts of the façade in order to reduce risk of damage. The lower parts of the façade below 4 m above street level, which are within reach of curious pedestrians and vulnerable to splashes from car traffic, were covered with glass panels.

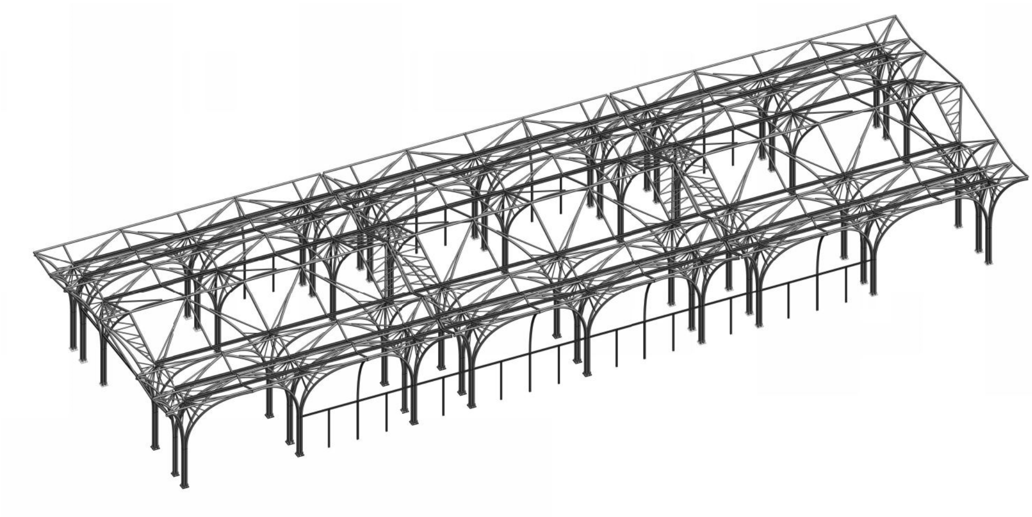

Fig. 4. A 3d view of the Piotrkowska Central Tram Station structure (from the Building Permit stage).

3. Project Development

The design of the canopy structure started in January 2013 on a "design and build" basis. BuroHappold Engineering acted as a consultant to Foroom (the Architect) who were employed directly by the general contractor of the whole modernization enterprise. The original architectural concept design from the competition stage envisaged the tram station canopy as a steel structure with an intricate geometry made of welded plates and featuring a roof covered with panels of coloured glass inspired by the Art Deco style.

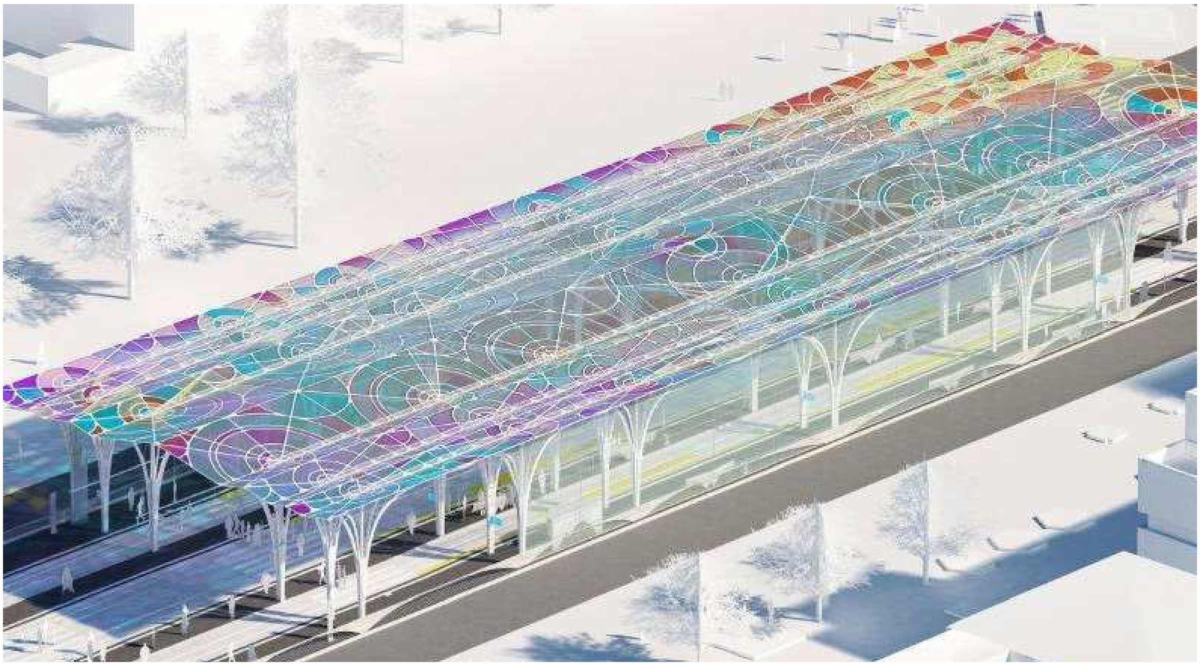

Fig. 5. Rendering of the Piotrkowska Central Tram Station (from the Architectural Concept stage). [1]

During the early concept the design team worked closely together to focus on challenges relating to the geometry. By linking different software a fully parametric 3d model was developed, which allowed an almost effortless process of form-finding and optioneering. Almost all geometrical parameters were variable in the model including:

- Column transverse and longitudinal spacing.
- Roof slopes.
- Arc angles, lengths and inclinations.
- Member cross-sections.

The aim of geometrical studies carried out during early concept was to find a compromise between architectural expression of the canopy and its structural efficiency. In order to reduce the quantity and variability of different connection details and labour-intensive prefabricated steel elements the geometry was made more regular. Roof slopes were carefully adjusted in order to minimize the snow accumulation effect and achieve an optimal distribution of snow loading over the roof surface. In addition, standard CHS profiles replaced custom welded steel sections from the architectural concept in order to improve cost-efficiency of the canopy structure. After a number of iterations the final geometry was agreed, which considered both static and visual aspects of the canopy. The 3d parametrical model became a common platform for further structural analysis and development of drawing documentation for all disciplines, ensuring the accuracy of the design and coordination as well as reducing time needed for reproducing the complex geometry starting from scratch.

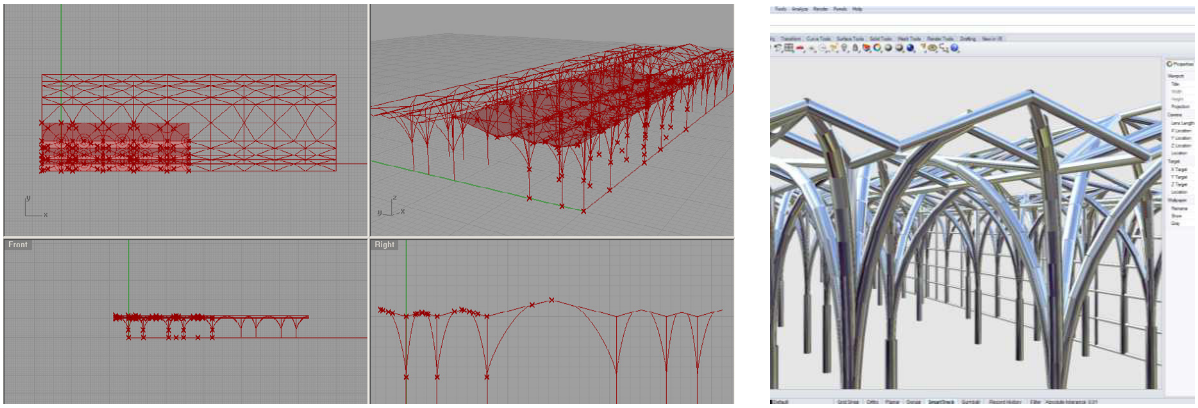

Fig. 6. Geometrical iterations in fully parametric 3d model; (left) framing model; (right) a view with CHS profiles.

Simultaneously the substructure for the glazed roof was under development. It was quickly identified that a secondary structure supporting the glazing and the coloured glass itself generates a number of challenges including:

- Strict limits on deflections for the glass-supporting structure to achieve a waterproof roof required stiff members which, in comparison to very light and elegant architectural concept, looked bulky when attempting to achieve spans in excess of 10 m.
- From the budget perspective and the glass assembly, cutting glass panels into intricate patterns would have been very inefficient.
- Regular rectangular substructure for the glazing did not fit well with the desired aesthetics of the smooth and organic canopy foreseen in the architectural concept design.
- The glazing support structure would be relatively heavy increasing the overall steel tonnage, impacting the design of the whole superstructure and substructure.

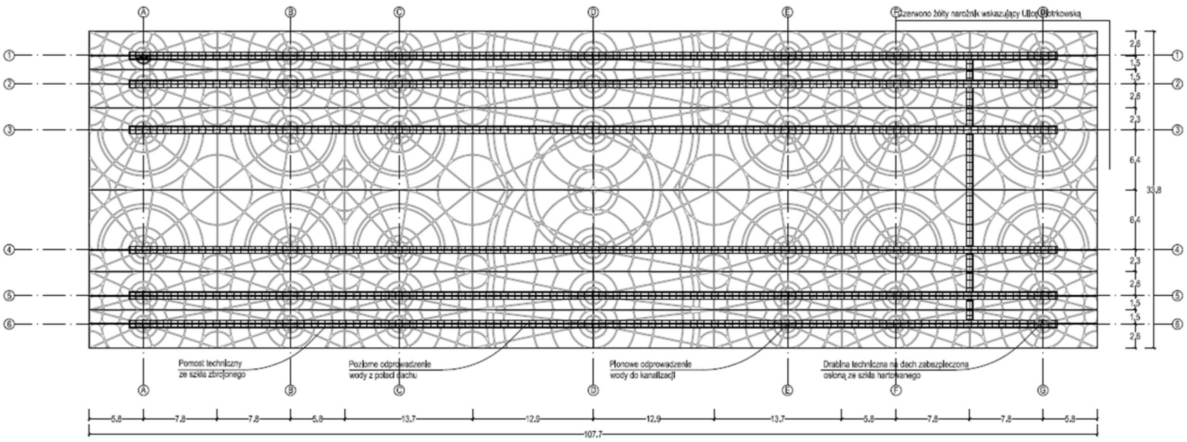

Fig. 7. Patterns of roof panels divisions (from the Architectural Concept stage). [1]

In order to satisfy the architectural vision and fit a reasonable budget in the same time, an open-minded approach was required. To address this vision, the BuroHappold team introduced the idea of swapping the glazing with a lighter material such as an ETFE membrane. This idea supported by a few examples of earlier BuroHappold lightweight projects was enthusiastically welcomed by the architect. The novel skin became a key element of the concept submitted on February 2013.

Once the building permit stage commenced in early Spring 2013 the design team had already identified main challenges relating to the new material, such as:

- A necessity for pre-stressed cables preventing the membrane from ponding.
- Detailing of the membrane and cables fixtures.
- Maintenance and snow removal issues.

After an initial assessment it was concluded that changing the roofing from a glass to an ETFE solution was mostly a beneficial decision, resulting in a more gentle, elegant and efficient structure. Once the contractor felt confident about the application of a new material and that a single layer ETFE solution could be resolved, the design team sought the support of a specialist lightweight membrane contractor who were to be officially involved in the design process. Employed by the contractor, Taiyo Europe was responsible for a further development of the membrane design, development of the printing technology and manufacture and construction of the ETFE cladding.

4. Wind and snow loads

The wind and snow loads were the most important cases in the design of the ETFE foil. The characteristic wind speed value according to the Polish code for a standard return period for the city region of Łódź is 20 m/s. Table 1 shows extreme wind pressure and suction values employed in the analysis.

Table 1. Wind loads envelope.

Membrane panel location	Pressure (*kPa*)	Suction (*kPa*)
Regular roof	0.30	0.12
Roof edges	-	0.70
Regular façade	0.45	0.25
Façade edges	0.33	0.33

In contrast to rather moderate wind loads, the snow loading was inevitably the critical load case. According to the Polish code the characteristic snow load value in this region is 0.9 kN/m^2 for a standard 50 year return period. In consideration of the roof geometry, the snow load on the roof varies from 1.49 kN/m^2 in the depressions and 0.86 kN/m^2 at ridges. The membrane design foresaw the requirement for pre-stressed cables to limit spans and deflections of the ETFE, yet the design team remained mindful of the possible augmentation of the snow load brought about by snow accumulation within the deformed geometry. In order to reduce this risk the figures quoted above include an agreed additional factor of 1.2. It is very unlikely that snow will exceed the assumed limits during the building's design life period, however such risks could never be fully excluded. So, in addition to designing for augmented loading, monitoring of the snow build-up was stipulated in the design and a snow removal strategy was developed. For the purposes of initial assessment of the snow weight a variety of settled snow scenarios were assessed. These considered thicknesses of snow layers taking into account different types of snow, as shown in table 2. The limits were given in regards to an average, factored snow load value.

Table 2. Snow cover volume weight and thickness.

Type of snow	Volume weight (*kg/m3*)	Thickness (*m*)
Fresh	100	1.80
Settled (a few hours/days after the fall)	200	0.90
Old (a few weeks/months after the fall)	350	0.50

5. Membrane design and manufacture

Throughout the concept design the material of the roof was accepted as a single layer 250 μm thick ETFE – ethylene tetra-fluor-ethylene (a fluoro-polymer plastic). Steel cables were introduced beneath the membrane in order to limit deflection and prevent ponding. The cables are stainless steel spiral strand with an average spacing of 80 cm and span between 2.85 m or 6.40 m along the whole canopy parallel to its longer axis. At each of longer bays an additional perpendicular cable was introduced providing an intermediate support for longitudinal cables in order to further help control of the membrane. The initial pre-stress force in cables is 10.0 kN thoughout, with peak tensions reaching up to 40.0 kN under critical load combinations.

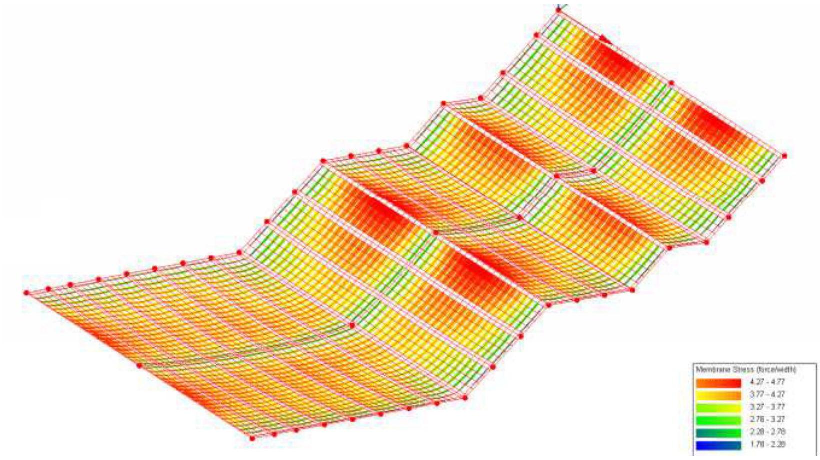

Fig. 8. Membrane forces of the typical long span strip of the roof. [3]

Such application of the ETFE can be found recently among different projects across the globe. However what makes this installation unique worldwide is the colourful pattern printed on the foil. The technology of colour printing on the ETFE was developed and tested by Taiyo. In 2014 a fabrication of a full scale prototype panel measuring 4 m by 2 m was completed, including the steel roof elements with the ETFE coloured skin. Its primary purpose was to examine the membrane performance over a year and ascertain the durability of the print exposed to changing environmental conditions over that period.

Fig. 9. The roof membrane prototype; (left) a view from above; (right) a view from below.

It was found that the prototype performance was satisfactory and the production of ETFE panels began. They were manufactured and printed in 1 m wide strips and bonded to create panels which were later assembled on the site. Pockets for the cables were incorporated within the welded seams to minimise the impact on the aesthetics.

6. Installation

Thanks to the lightweight membrane design the installation of the colourful skin, commenced in Spring 2015, was comparatively effortless in comparison to the assembly of the heavy glass panels previously envisaged. ETFE sheets were delivered to site in rolls which could be lifted with ropes by two men. A team of ten trained rope access specialists were employed for this job.

Fig. 10. The membrane installation.

Once each roll was positioned at its allotted location it was deployed and fixed using aluminium extrusions attached along the steel members of the roof structure. During this process the ETFE skin had to be stretched by the crew to introduce an initial pre-stress into the membrane. The aforementioned cables were pulled through the pockets incorporated in the ETFE and connected to the steel superstructure via standard end fittings. Cable prestress was then introduced by adjusting their length, minimising any residual sag in the panels.

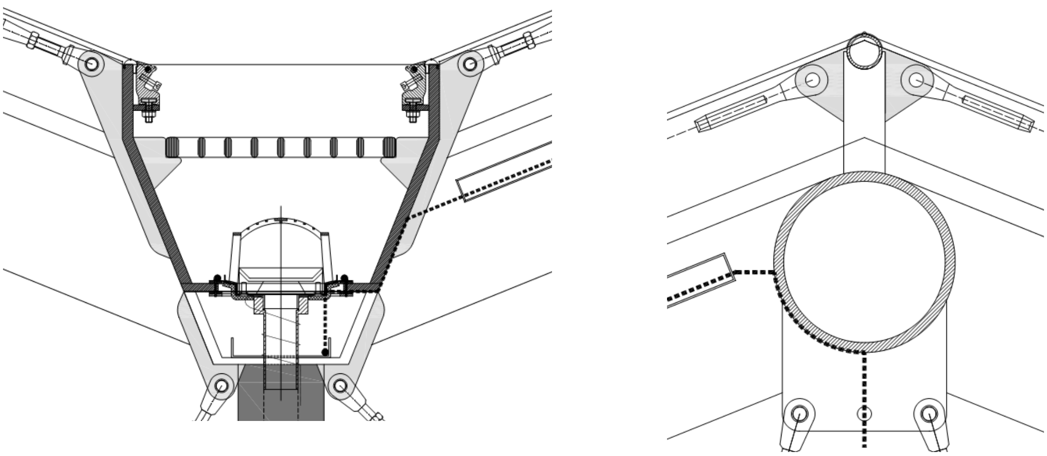

Fig. 11. Samples of cable connection details; (left) a gutter detail; (right) a ridge detail. [2]

The geometrical complexity of the superstructure – its tall arcs, long-span beams and complicated connection details – was undoubtedly going to be a challenge to achieve with perfect precision when allowing for real world tolerances. For a glass solution, any unforeseen combination of these imprecisions might present a situation where a panel would not fit at all, leading to either serious or time consuming amendments to the steel on site or lengthy re-manufacture of bespoke glass panels. To the benefit of the Contractor, the ETFE membrane was able to accommodate larger tolerance issues than anticipated, within acceptable limits, due to its elasticity and this avoided delay.

Fig. 12. The canopy under construction.

7. Maintenance

The design allowed for technical access to the top of the roof from a scissor lift, with four catwalks located over main gutters running along the length of the whole canopy. In addition to this, climbing handles and safety lines were incorporated over the whole roof. For the purpose of snow removal aluminum ladders with plastic protectors on the sharp edges (preventing inadvertent damage to the membrane) can be placed on the roof between parallel gutters. To minimize the access frequency for snow removal and thus reduce risk of damage to the membrane and any hazard to operatives, each of the gutters is equipped with a heating wire to assist snow melt when required, which is subsequently fed to drainage pipes to the sewage system under the street level.

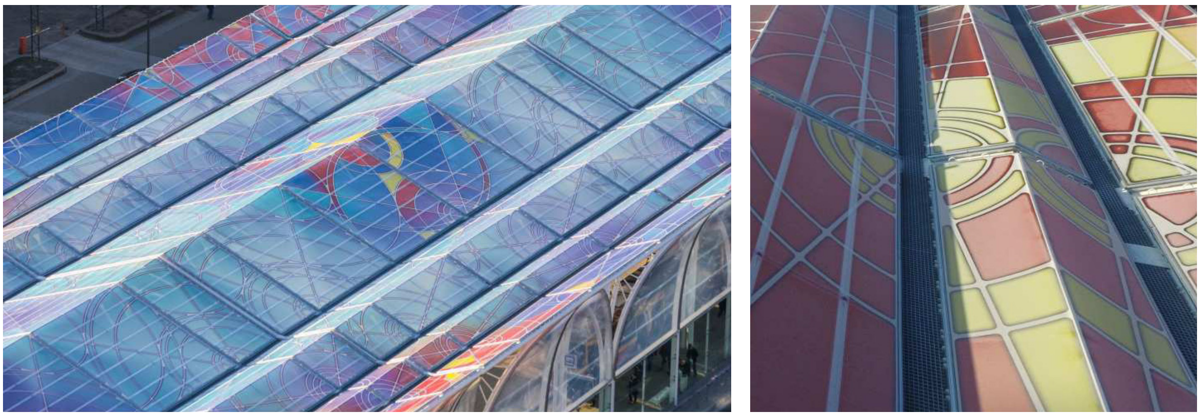

Fig. 13. (left) A bird's eye view of the roof; (right) the catwalks in main gutters.

8. Conclusions

The ETFE membrane provided simple yet significant improvement to the Piotrkowska Central Tram Station canopy. The success of this novel skin owes much to the openness of the design team (considered as a whole – the Architects and the Engineers) and their willingness to investigate alternatives for the betterment of the canopy. Working in a 3d environment was essential in order to tackle such intricate geometry and investigate options quickly. This especially the case during later stages of the design where the coordination between steel superstructure and membrane details helped to bring this visionary project to life without any major issues, despite the inevitable challenges faced during construction. Without any doubt the idea of applying the ETFE membrane instead of glass contributed much to the success of the Piotrkowska Central Tram Station, which not only serves citizens of Łódź well as a comfortable addition to the public transportation system, but which is quickly becoming one of the iconic features of the city.

Fig. 14. The Piotrkowska Central Tram Station by night.

Acknowledgements

Image credits (all images copyright): Jan Gałecki, *figs 5,7*. Jan Gałecki/Taiyo Europe, *figs 2,9,13,14*. Foroom *fig 11*. Taiyo Europe/ konstructAG, *fig 8*. BuroHappold Engineering *figs. 1,3,4,6,10,12*.

Project credits for the Piotrkowska Central Tram Station:
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Author of the architectural competition: Jan Gałecki
General Contractor: Mosty-Łódź
Design Team:
Foroom – architect (Bartłomiej Grotte, Rafał Jedliński, Maciej Pędzich, Konrad Waligóra, Jan Gałecki);
BuroHappold Engineering – structural engineer and membrane concept,
in cooperation with BPI Profil-Projekt - steel structure detail design;
Taiyo Europe – membrane design and manufacture,
in cooperation with konstruct AG – membrane engineer.

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[1] Architectural competition, Jan Gałecki, Łódź 2012
[2] Architectural execution design, Foroom sp. z o.o., Warsaw 2014
[3] Static calculation ETFE-foil & cables, konstruct AG, Rosenheim 2013.